Bently's Corner

RUBS RESEARCH

Studies reveal physical phenomena of rotor rubs

By Donald E. Bently, President and Chairman

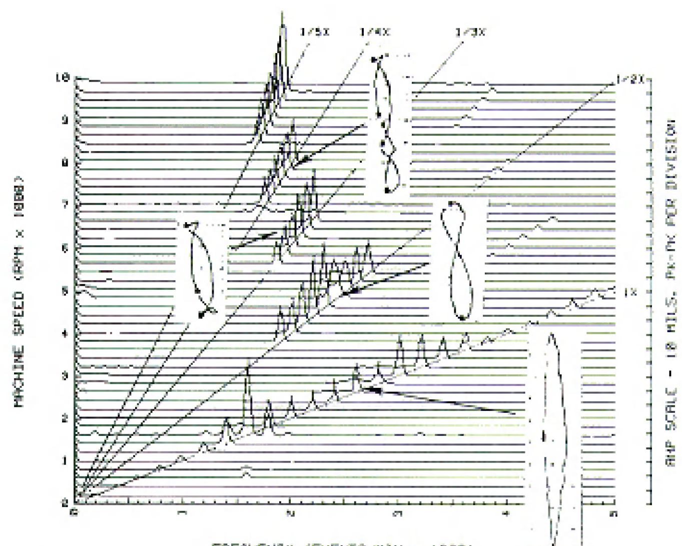

FIGURE 1

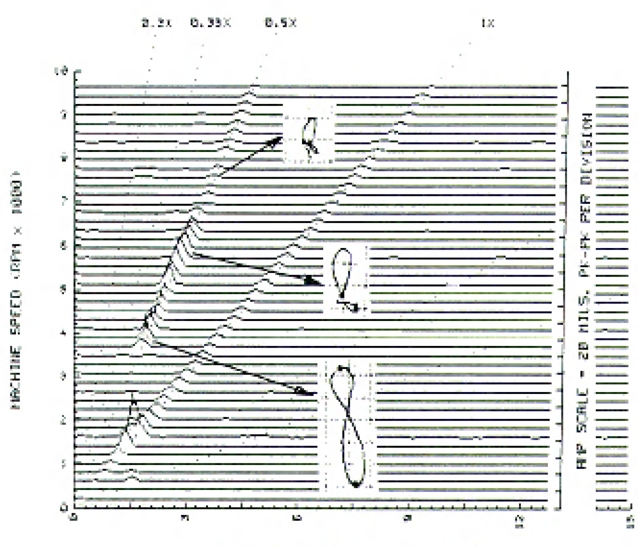

FIGURE 2

It is well known that rotating machinery rubs, which occur when a rotor enters contact with a stationary part of the turbomachine, is potentially devastating. Yet, little has been accomplished in determining the physical phenomena related to rubs and in learning how to predict and control rotor rubs.

Studies conducted by Bently Rotor Dynamics Research Corporation are leading us closer to solutions to these problems. Although theoretical studies have been performed in the past on the physical characteristics of rubs, actual

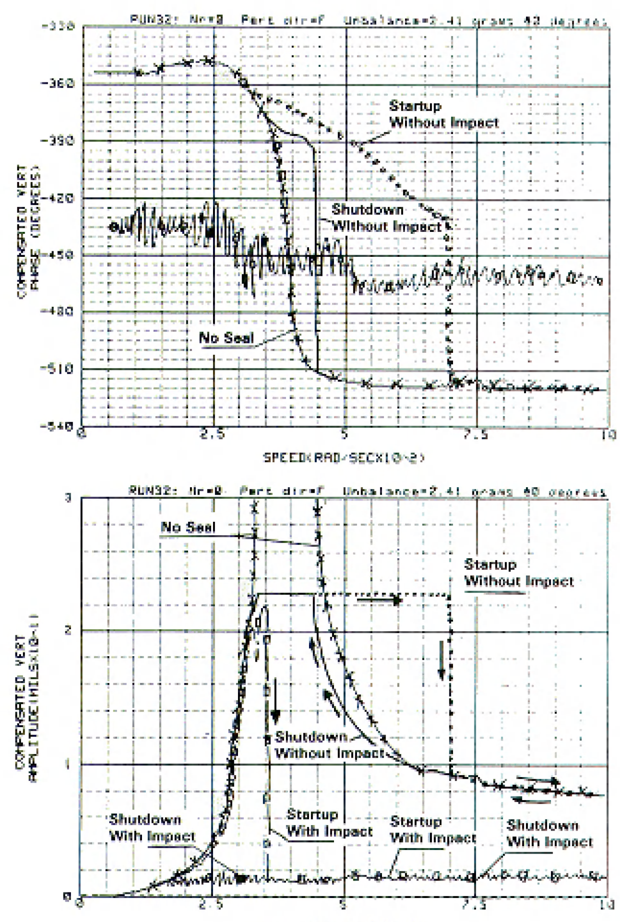

FIGURE 3

laboratory documentation of these characteristics has been lacking. Our studies attempted to relate all experimentally-observed and -documented phenomena in rotor response to rubs to the physical sources generating and controlling them.

A simple rotor lateral vibration model was constructed in which the physical causes of rubs—friction, impact, and modification of rotor stiffness—were present. Using this model, two types of rubs were investigated: partial rubs, which occur when the rotor occasionally touches a stator, and full annular rubs, which occur in seals.

On a real machine, both types of rubs can take place separately or simultaneously. Partial and full annular rubs also display similar physical phenomena.

A partial rub usually precedes a full rub. Partial rubs are often of the "hit and bounce" variety, meaning that rub conditions change in nature as rotor-stator contact begins to act as a new dry, non-lubricated bearing (which is a poor bearing). As the rub progresses, the rotor comes into contact with the stationary part of the machine for increasingly longer periods of time. This causes the rigidity of the system and friction force to increase rapidly.

A full rub may make the shaft move in counter-rotation. This reverse precession is generated by friction force which is applied to the rotor in a tangential direction at the point of contact. The tangential force creates a torque opposite to the direction of shaft rotation. (Unbalance creates a force that is normal to the contact surface.) When the torque becomes very large, as in a full annular rub condition, the shaft begins to move in counter-rotation.

Partial rub study results

Our studies of partial rubs revealed that forward subharmonic vibrations were dominant and that the rotor response has two main components: 1X and subharmonic vibration. The subharmonic vibrations occurred in a pattern relative to the actual rotative speed of the machine.

With higher rotational speed, lower fractions of subharmonic vibration can occur. The frequencies of the subharmonic vibrations were fractions of the rotational speed (ω, $\omega/2$, $\omega/3$,...) and were related to impact and after-impact rotor free lateral vibrations. When a partial rub occurred, the subsynchronous vibrations were exactly 180° out of phase between the vertical and horizontal rotor response (which reduced the orbit to a straight line).

Figures 1 and 2 are Cascade plots of a partial rub. They show the spectrum of rotor vibrations versus rotational speed and corresponding orbits. The subharmonic vibrations excited by the partial rub are evident.

Figure 1 shows the results of the lower rub force and the appearance of subharmonics 1/2, 1/3, and 1/4. Figure 2 shows the results when a higher rub force was applied. The subharmonic vibrations of $(\omega/2)$X exist in the large region of the rotative speed.

Full annular rub study results

Mathematical models of the vibrations related to the full annular rub of a shaft predict two main phenomena: a 1X precession which corresponds to the unbalance inertia force and the existence of self-excited vibrations in the

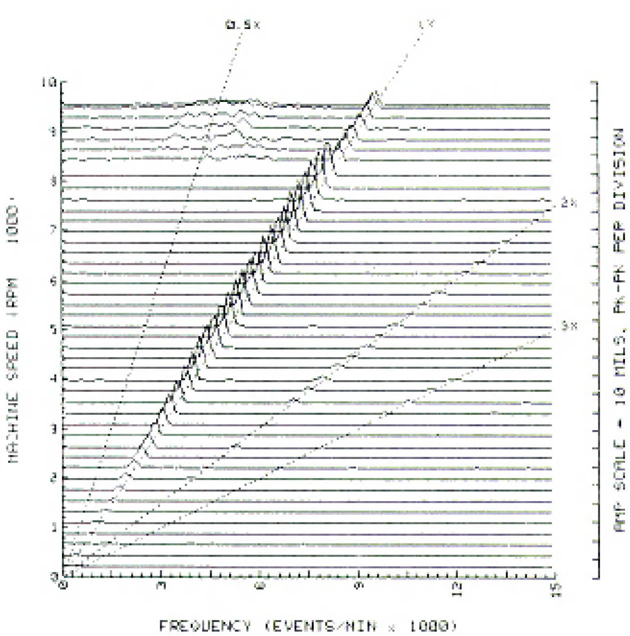

FIGURE 4

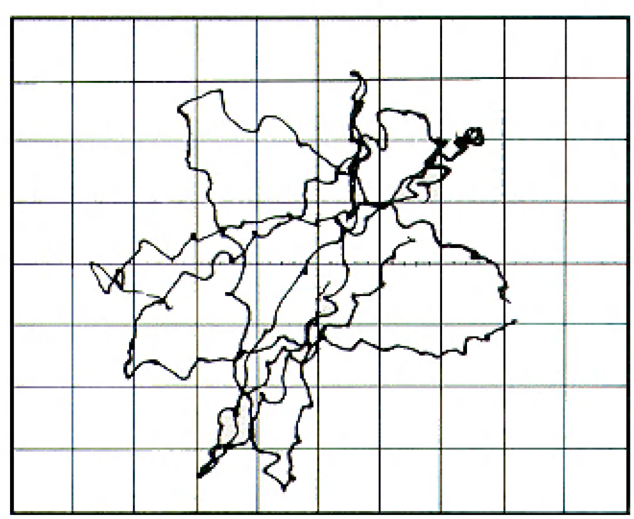

FIGURE 5

form of backward precession. Our experiments confirmed these theoretical predictions.

Although 1X precession and backward precession do not take place simultaneously, they can switch from one regime to the other. Figure 3 is a comparison of the synchronous response of the rotor to the full annular rub during runup and rundown. The Bode' plot shows the existence and disappearance of both regimes. The switch to backward precession from 1X vibrations was obtained by using a rubber hammer to cause slight excitation of the rotor.

The self-excited vibrations caused by the full annular rub were related to the nonlinear geometric features of the rotor as well as to dry friction at the rotor/seal surfaces.

The backward precession was quite violent and can occur in the entire range of rotational speed. Backward precession can totally destroy a rotor. High friction causes the grinding of the rotor surface, and the rotor uses much more energy than under a normal load condition. This leads to considerable changes in the torque/rotational speed relationship.

Figures 4 and 5 were made of the full annular rub on the same runup of the rotor model. Figure 4 is a Cascade plot of the rotor's response to the full annular rub. It shows the the dominance of the synchronous precession and the presence of harmonics.

Figure 5 shows the shaft pattern under a full annular rub condition. The rotor bounces around the seal several times during one period of rotation. Higher harmonics are also present.

Figures 6 and 7 are Cascade plots of the full annular rub during runup and rundown. The self-excited backward precession begins at the rotative speed just below the first balance resonance and is maintained during rundown even at very low speed. The regime appears very stable, and the synchronous component is small. There is no evidence of 1X resonance.

The role of friction and stiffness modification

The main physical phenomenon in the partial rub is the interference of the free vibration during the bouncing motion. In the partial rub, friction also played an important, although not a primary, role in the physical phenomena reflected in the rotor response. Friction modified quantitatively the rotor motion, causing a partial rub.

Friction, however, is fully responsible for the self-excited backward precession during full annular rub conditions. As a nonlinear phenomenon, friction is also responsible for generating multiharmonic responses that contain higher harmonics.

When the rotor periodically enters into contact with an obstacle, the modification of stiffness causes subharmonic vibrations of the order 1/2 as well as higher harmonics in the rotor response. Using the simple linear model, we were able to accurately predict the existence of 1/2X subharmonic vibrations and the rotor instability.

Many questions remain to be answered on rotor rubs, however. Further insight is needed into the physical phenomena of rubs. These answers should lead to a solution which will enable us to predict and control rotor rubs and, thus, protect the operational integrity of turbomachinery.

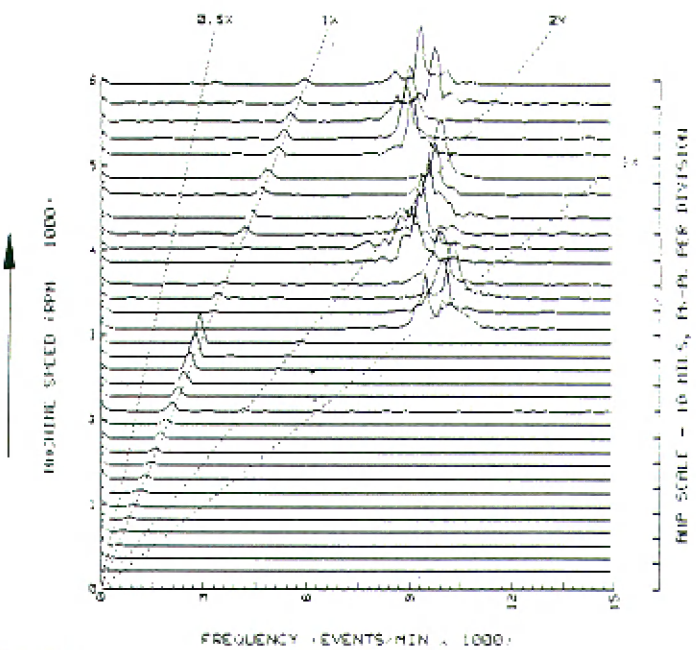

FIGURE 6

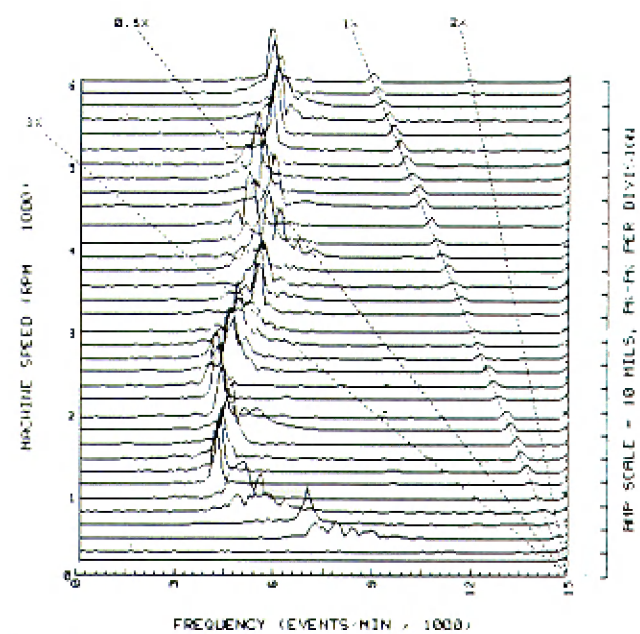

FIGURE 7